Updated Coastal DEMs of Midway Atoll

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In May 2012, NOAA's National Geophysical Data Center (NGDC) updated the integrated bathymetric-topographic digital elevation models (DEMs) of Midway Atoll that it built in June 2009 to support NOAA's Tsunami Program [Grothe et al., 2010]. The new 1/3 arc-second (~10 meter) and 3 arc-second (~90 meter) DEMs incorporate new, high-resolution topographic lidar data collected by the U.S. Geologic Survey (USGS) in 2010 [Krause et al., 2012]. These lidar data were graciously provided to NGDC by Michelle Reynolds, USGS, as a cleaned, 1-meter cell size, bare-earth DEM. A new coastline of Sand Island and Eastern Island (collectively called Midway Island) was also digitized by hand to align with the new lidar data. DEM development methodology and other data sources used in building the version 2 Midway Atoll DEMs are as described in Grothe et al. [2010]. The version 2 Midway Atoll DEMs were used by NOAA's Pacific Marine Environmental Laboratory to develop an improved tsunami forecast model for Midway Atoll [Gica, 2012].

References

Grothe, P.R., L.A. Taylor, B.W. Eakins, K.S. Carignan, E. Lim, R.R. Warnken, and R.J. Caldwell, 2010. *Digital Elevation Models of Midway Atoll: Procedures, Data Sources and Analysis*, NOAA Technical Memorandum NESDIS NGDC-33, Dept. of Commerce, Boulder, CO, 24 pp. (http://www.ngdc.noaa.gov/dem/squareCellGrid/getReport/642)

Gica, E., 2012. *Development of a Tsunami Forecast Model for Midway Atoll, USA,* NOAA Pacific Marine Environmental Laboratory technical report, Seattle, WA, 63 pp. (http://nctr.pmel.noaa.gov/forecast_reports/draft_reports/MidwayAtollFM12222012v2-web.pdf)

Krause, C.M., K.N. Courtot, P. Berkowitz, J. Carter, and M.H. Reynolds, 2012. Climate Change Vulnerability Assessment of the Low-Lying Northwestern Hawaiian Islands, in Reynolds, M.H., P. Berkowitz, K.N. Courtot, and C.M. Krause, eds., *Predicting sea-level rise vulnerability of terrestrial habitat and wildlife of the Northwestern Hawaiian Islands*, U.S. Geological Survey Open-File Report 2012–1182, 139 pp. (http://pubs.usgs.gov/of/2012/1182/).

NOAA Technical Memorandum NESDIS NGDC-33

DIGITAL ELEVATION MODELS OF MIDWAY ATOLL: PROCEDURES, DATA SOURCES AND ANALYSIS

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Also available from the National Technical Information Service (NTIS)
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Digital Elevation Models of Midway Atoll: Procedures, Data Sources and Analysis

1. Introduction

In June 2009, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed two integrated bathymetric–topographic digital elevation models (DEMs) centered on Midway Atoll for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov). The coastal DEMs will be used as input for the Method of Splitting Tsunami (MOST) model development by PMEL to simulate tsunami generation, propagation and inundation. A 3 arc-second DEM[1] (Fig. 1) was generated from diverse digital datasets in the region (grid boundary and sources shown in Fig. 4) and will be used for tsunami modeling, as part of the tsunami forecast system Short-term Inundation Forecasting for Tsunamis (SIFT) developed by PMEL for the NOAA Tsunami Warning Centers. To increase the forecasting accuracy of SIFT, a smaller 1/3 arc-second DEM (Fig. 2) was generated for the immediate area surrounding Midway Atoll, where high-resolution bathymetry multibeam data were available. This report provides a summary of the data sources and methodology used in developing the Midway Atoll DEMs.

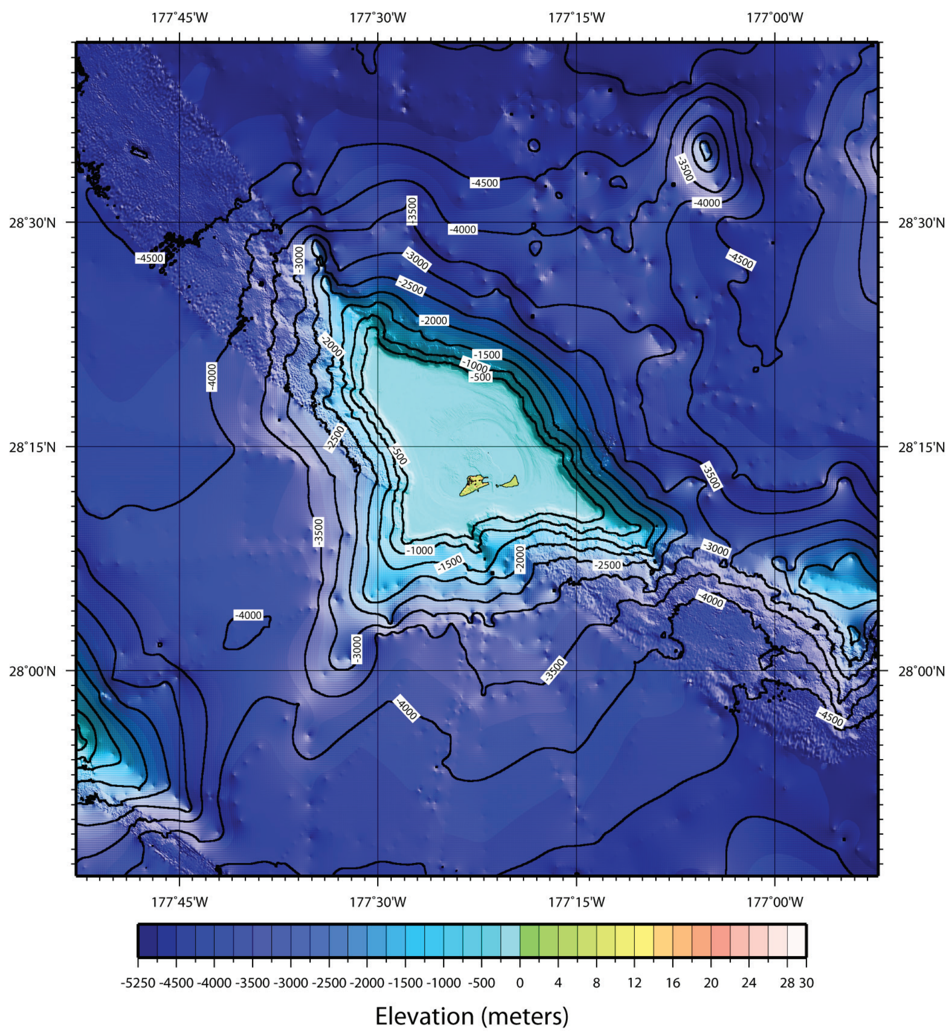

Figure 1. *Shaded-relief image of the 3 arc-second Midway Atoll DEM. Contour interval is 500 meters for bathymetry and 20 meters for topography.*

1. The Midway Atoll DEMs are built upon a grid of cells that are square in geographic coordinates (latitude and longitude), however, the cells are not square when converted to projected coordinate systems, such as UTM zones (in meters). At the latitude of Midway Atoll (28°13'N, -177°21'W) 1/3 arc-second of latitude is equivalent to 10.26 meters; 1/3 arc-second longitude equals 9.09 meters. Three arc-seconds of latitude is equivalent to 92.35 meters; 3 arc-seconds of longitude is equivalent to 81.80 meters.

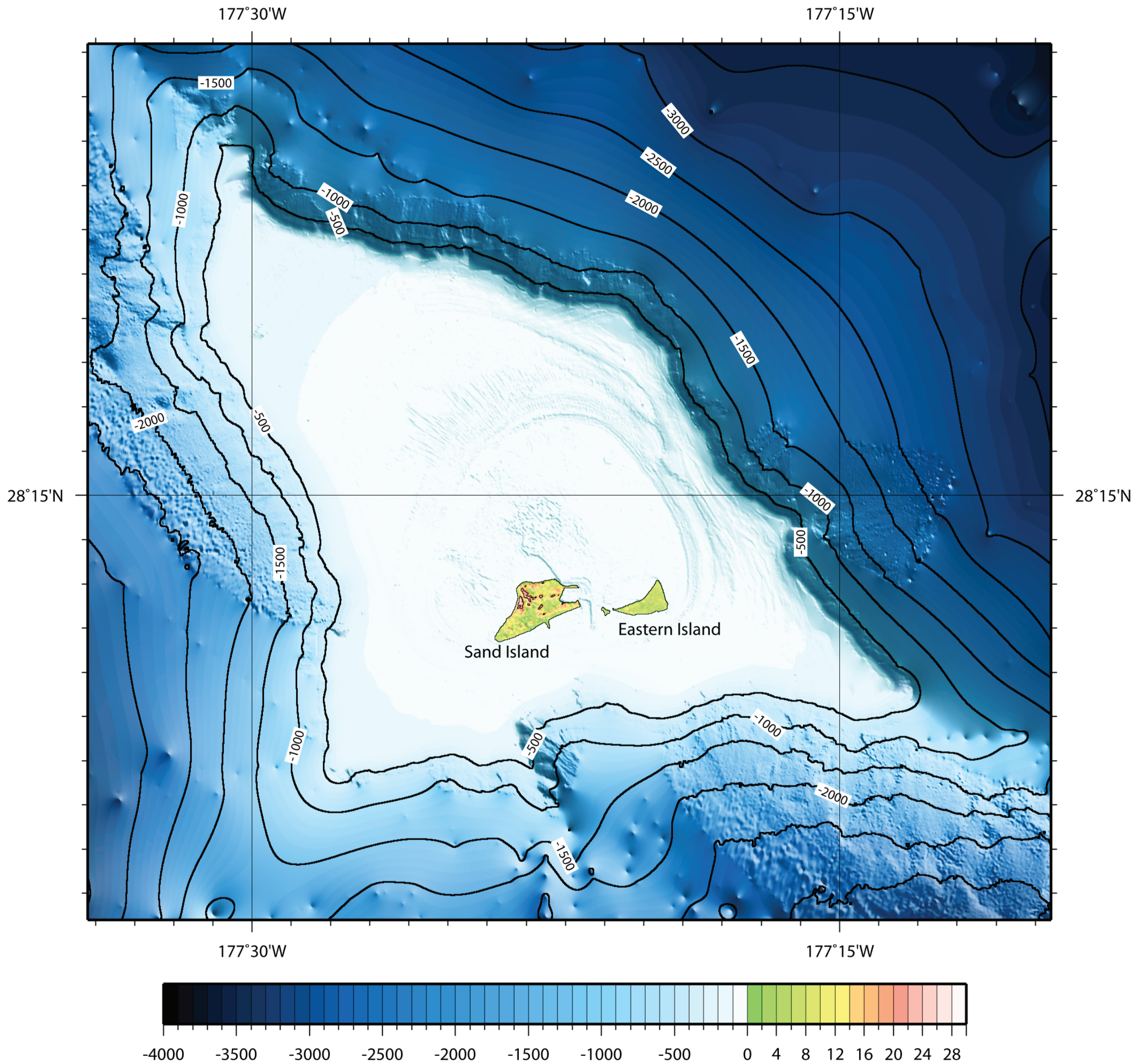

Figure 2. *Shaded-relief image of the 1/3 arc-second Midway Atoll DEM. Contour interval is 500 meters for the bathymetry and 20 meters for the topography.*

2. STUDY AREA

Midway Atoll is a circular atoll that consists of two islands, Sand Island and Eastern Island, collectively called Midway Island. The atoll is located in the Hawaiian archipelago approximately 1,150 miles west-northwest of Hawaii (Fig. 3). In 1940, an air and submarine base were built on the island. The island gained notoriety in 1942 after the Battle of Midway proved to be the turning point of WWII. In 2006, Midway Island was designated as a national monument with the other Northwestern Hawaiian Islands, and is managed by the U.S. Fish and Wildlife Service and NOAA.

Midway Atoll formed from a shield volcano that developed around 28 million years ago from the same hotspot that is located under Hawaii today. Pacific plate motion has moved the volcano northwest from the hotspot, where it has slowly subsided. A coral reef has grown around the rim of the atoll, which is currently 160 meters thick and is comprised of post-Miocene limestones and upper-Miocene sediments overlying basalt.

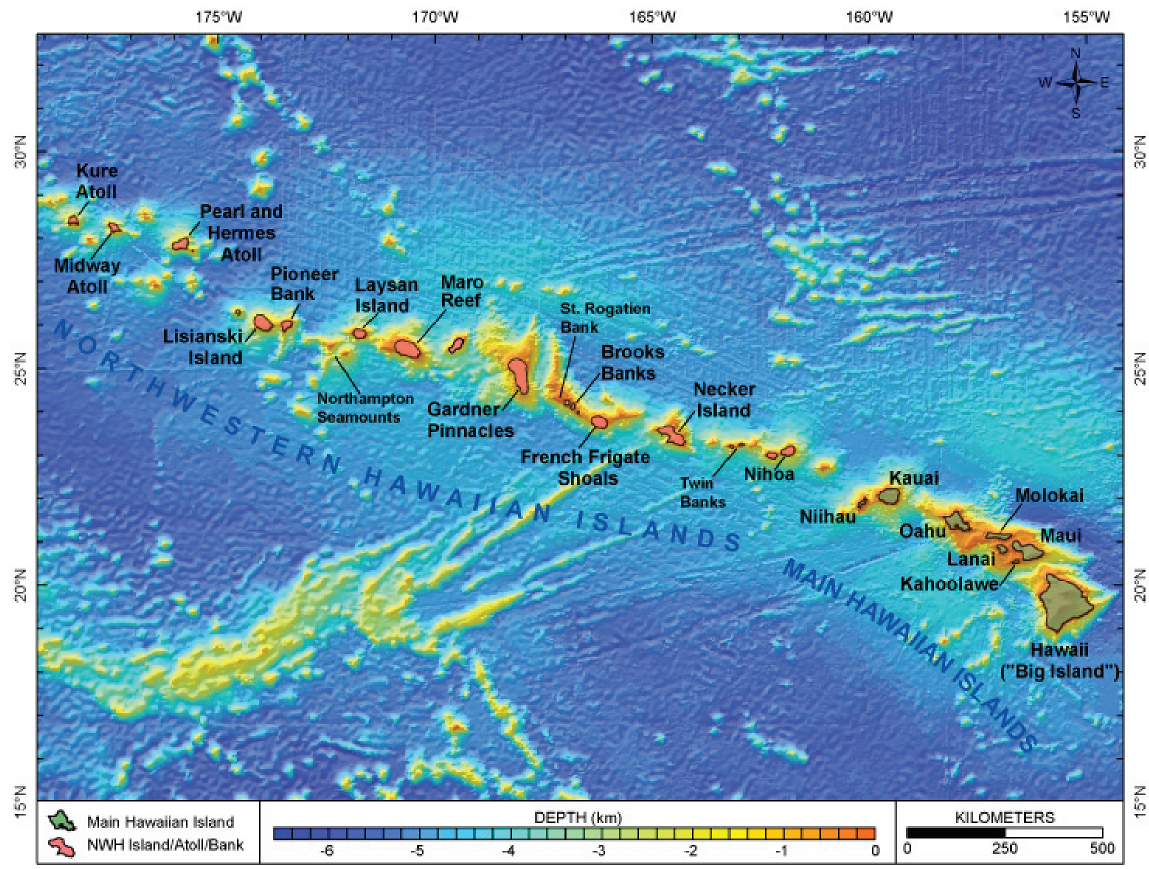

Figure 3: *Location of Midway Atoll in the Northwestern Hawaiian Island Chain.*
(Image credit: University of Hawaii at Manoa; http://www.soest.hawaii.edu/pibhmc/pibhmc_nwhi.htm)

3. Methodology

The Midway Atoll DEMs were constructed to meet PMEL specifications (Tables 1a and 1b), based on input requirements for the development of reference inundation models (RIMs) and standby inundation models (SIMs) (*V. Titov, pers. comm.*) in support of NOAA's Tsunami Warning Centers use of SIFT to provide real-time tsunami forecasts in an operational environment. The best available digital data were obtained by NGDC and shifted to common horizontal and vertical datums: World Geodetic System of 1984 (WGS 84) geographic and mean high water (MHW), respectively, for modeling of maximum flooding. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

Table 1a: PMEL specifications for the 3 arc-second Midway Atoll DEM.

Grid Area	Midway Atoll
Coverage Area	177.88º to 176.87º W; 27.77º to 28.70º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System of 1984 (WGS 84)
Vertical Datum	Mean high water (MHW)
Vertical Units	Meters
Cell Size	3 arc-second
Grid Format	ESRI Arc ASCII grid

Table 1b: PMEL specifications for the 1/3 arc-second Midway Atoll DEM.

Grid Area	Midway Atoll
Coverage Area	177.57º to 177.16º W; 28.09º to 28.42º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System of 1984 (WGS 84)
Vertical Datum	Mean high water (MHW)
Vertical Units	Meters
Cell Size	1/3 arc-second
Grid Format	ESRI Arc ASCII grid

3.1 Data Sources and Processing

Shoreline, bathymetric, and topographic digital datasets (Fig. 4) were obtained from several U.S. federal agencies including: NOAA's NGDC, Office of Coast Survey (OCS), and the Center of Coastal Monitoring and Assessment (CCMA); the U.S. Geological Survey (USGS); and the Naval Postgraduate School. Safe Software's (http://www.safe.com) *FME* data translation tool package was used to shift datasets to WGS 84 horizontal datum and to convert them into ESRI (http://www.esri.com) *ArcGIS* shapefiles. The shapefiles were then displayed with *ArcGIS* to assess data quality and manually edit datasets. Vertical datum transformations to MHW were accomplished using *FME* and *ArcGIS*, based upon data from NOAA tide station #1619910 Sand Island, Midway Island. Applied Imagery's *Quick Terrain Modeler* software (http://www.appliedimagery.com) was used for evaluating datasets before the final gridding process.

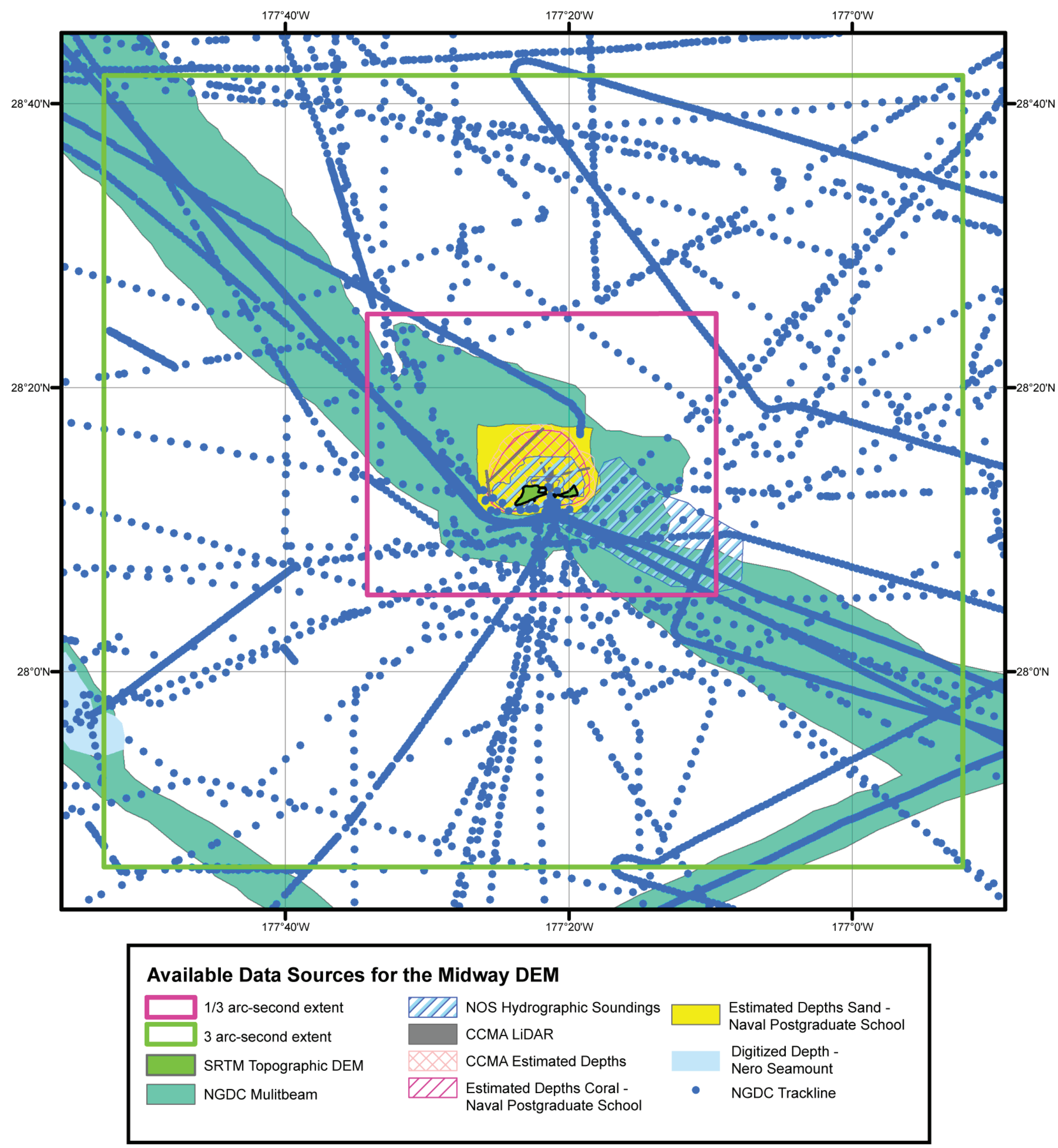

Figure 4. *Source and coverage of datasets available in the Midway Atoll region. Areas of no data are white. National Ocean Service (NOS) and CCMA surveys were not used in DEM development.*

3.1.1 Shoreline

There were no NOAA Electronic Nautical Charts (ENCs) or high-resolution coastline datasets available for Midway Island. Therefore, NGDC digitized the coastline based on NOAA Raster Nautical Chart (RNC) #19481 (Table 2).

Table 2: Shoreline dataset used in the Midway Atoll DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Coordinate System*	*URL*
NOAA RNC #19481	2009	Vector	1:32,500	WGS 84 geographic	MHW	http://www.nauticalcharts.noaa.gov/mcd/Raster

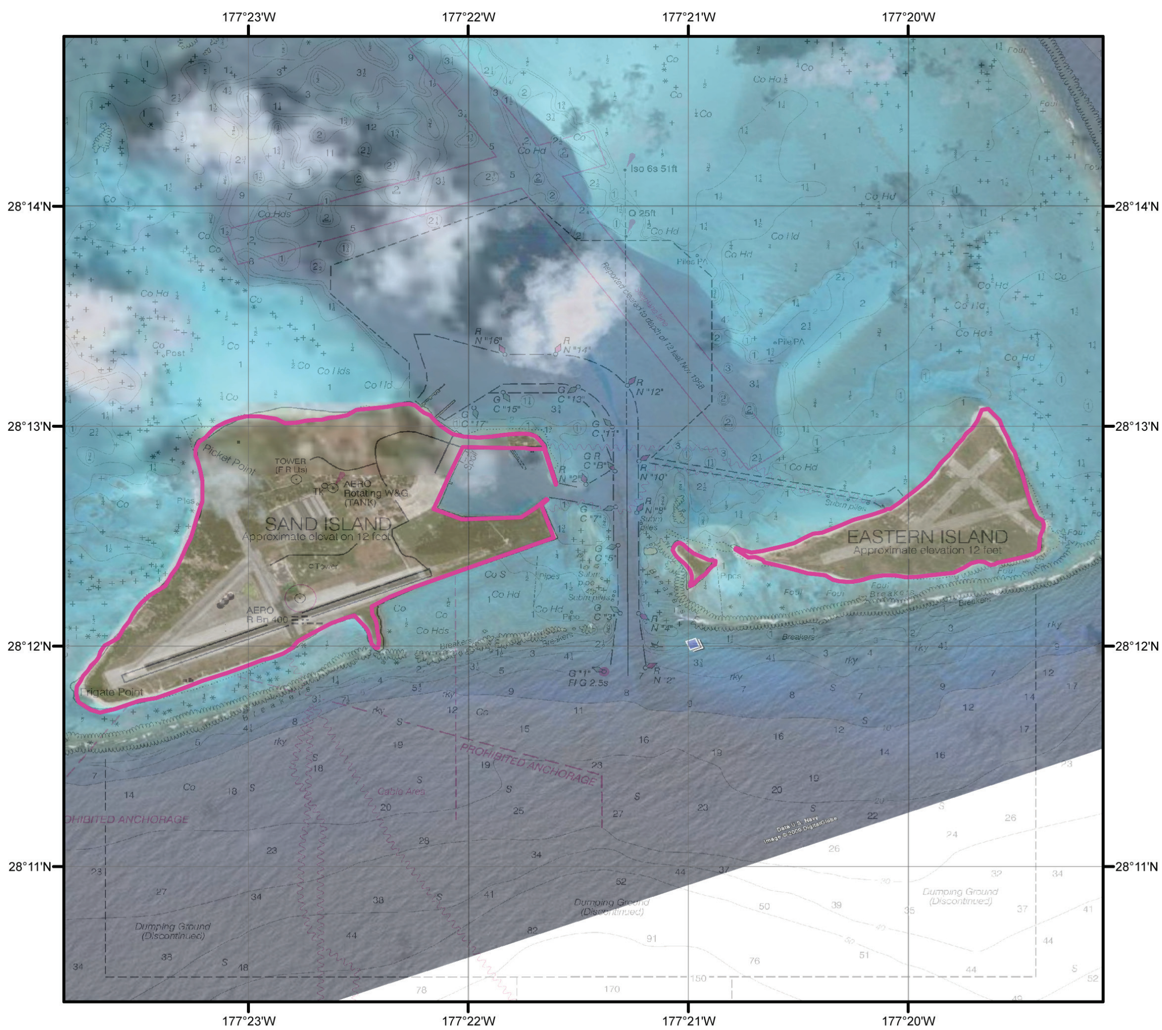

Figure 5. *Satellite image (2007) of Midway Island, extracted from Google Earth. Final coastline in pink.*

1) NGDC digitized coastline

NGDC digitized the Midway Island coastline from NOAA RNC #19481 (Table 3), which has a resolution of 1:32,500. NOAA RNC #19482 has higher resolution but was not used in digitizing the final coastline because significant coastal morphologic changes have occurred since 2000 (Fig. 6). *Google Earth* satellite imagery (2007) and the shallow-water Naval Postgraduate School's estimated depths (2006) were used to adjust the final coastline to match present morphology.

Table 3: NOAA nautical charts available for Midway Atoll.

Chart	*Title*	*Edition*	*Edition Date*	*Format*	*Scale*
19480	Gambia Shoal to Kure Atoll	9th	2007	RNC	1:180,00
19481	Midway Islands	11th	2005	RNC	1:32,500
19482	Midway Islands	9th	2000	RNC	1:10,000

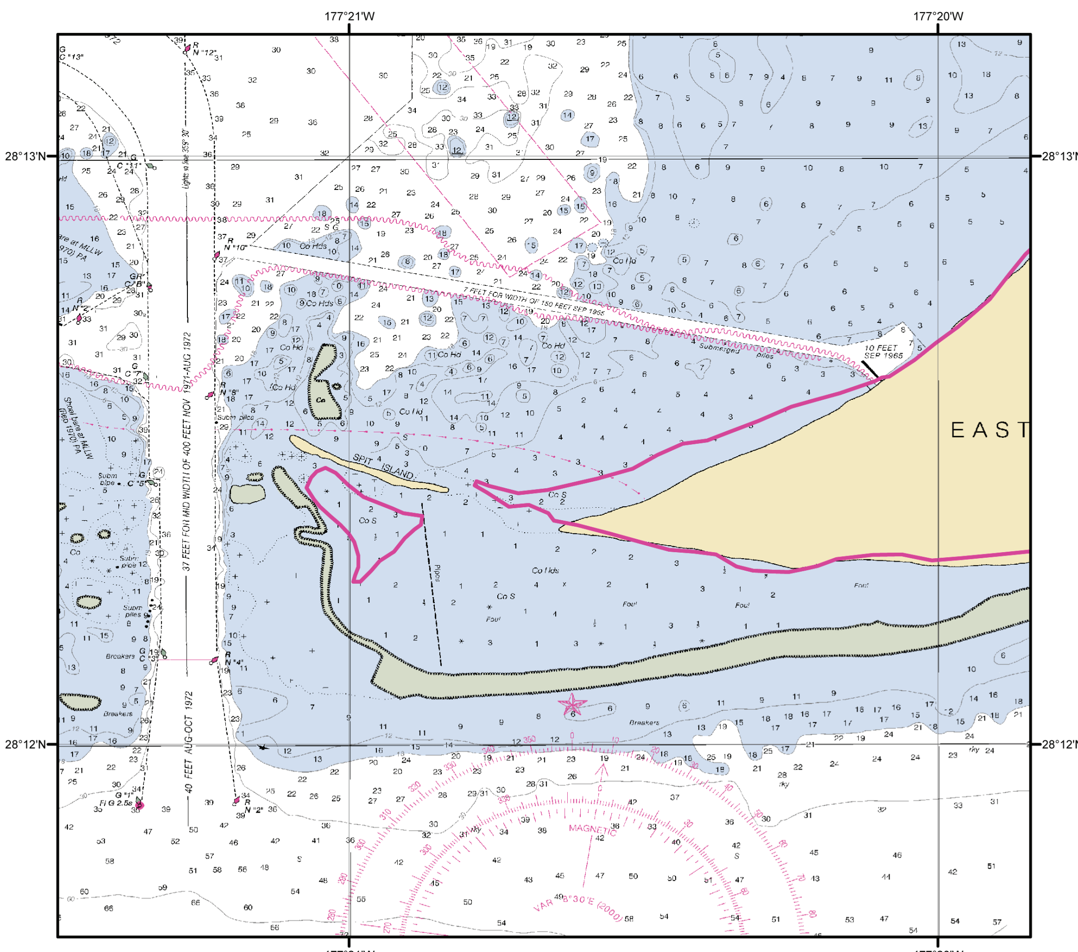

Figure 6. *Example of coastal morphologic change since 2000. NOAA RNC #19482 (2000) in background shows major differences in the sand spit from the final coastline (in pink), which was derived from NOAA RNC #19481 (2005) and Google Earth Satellite imagery (2007).*

3.1.2 Bathymetry

Bathymetric datasets available for the compilation of the Midway Atoll DEMs include five multibeam swath sonar surveys from the NGDC multibeam sonar database, three National Ocean Service (NOS) hydrographic surveys, 28 trackline geophysics surveys, CCMA bathymetric lidar surveys and estimated depths extracted from satellite imagery, and the Naval Postgraduate School's (NPS) estimated depths extracted from satellite imagery (Table 4; see Figs. 4, 7;). The NOS hydrographic soundings (1941) and CCMA's estimated depths from satellite imagery (2002) and bathymetric lidar data (2001) were not used in DEM development because they have been superseded by more recent, higher-resolution data.

Table 4: Bathymetric datasets used in compiling the Midway Atoll DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
NGDC	1992 to 2005	Multibeam sonar swath files	Raw MB files gridded to 1/3 arc-second	WGS 84 geographic	Assumed mean sea level (MSL)	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html
NGDC	1961 to 1991	Trackline (single beam echo-sounder)	Soundings up to 100's of meters along profile with profiles spaced kilometers apart	WGS 84 geographic	Assumed MSL	http://www.ngdc.noaa.gov/mgg/geodas/trackline.html
NPS	2006	Estimated Depths from Satellite Imagery	3 to 5 meters	WGS 84 geographic	Assumed MSL	
NOAA RNC 19480	2009	Digitized Points	1:180,000	WGS 84 geographic	MHW	http://www.nauticalcharts.noaa.gov/mcd/Raster

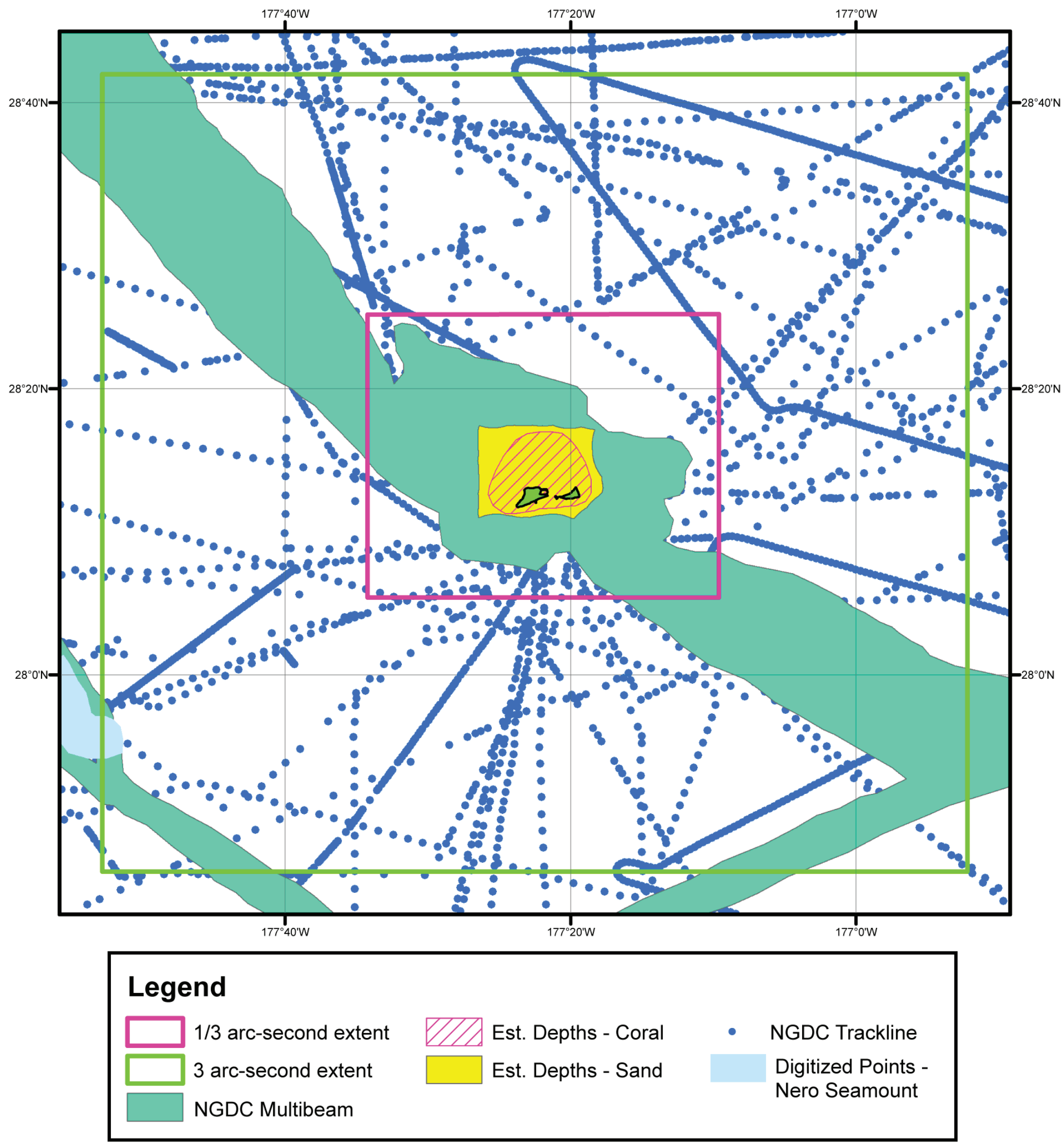

Figure 7. *Spatial coverage of bathymetric datasets used to compile the Midway Atoll DEMs. Areas of no data are white. Final coastline is illustrated in black.*

1) **Multibeam swath sonar surveys**

Five multibeam swath sonar surveys were available from the NGDC multibeam bathymetry database for use in the Midway Atoll DEMs (Table 5, Fig. 8). This database is comprised of the original swath sonar surveys conducted mostly by the U.S. academic fleet. The data were gridded to 1/3 arc-second resolution using *MB-System*[2]. *MB-System* is an NSF-funded free software application specifically designed to manipulate multibeam swath sonar data. After assessing individual survey quality, the gridded data were transformed to MHW (see Sec. 3.2.1) and shapefiles for editing in *ArcMap*. NGDC edited out noise along the swath edges and then converted to xyz format using *FME* for gridding of the preliminary bathymetric surface and final grid.

Surveys HI-05-03 and AHI-03-06 provide high-resolution coverage surrounding Midway Atoll but do not include the shallower region inside the atoll. The other three surveys are transits rather than dedicated sea-floor surveys. All have a horizontal datum of WGS 84 geographic and undefined vertical datum, which was assumed to be essentially mean sea level (MSL).

Table 5: Multibeam swath sonar surveys used in compiling the Midway Atoll DEMs.

Cruise ID	*Ship*	*Year*	*Original Vertical Datum*	*Original Horizontal Datum*	*Institution*
AVON-06MV	Melville	1999	Assumed MSL	WGS 84 geographic	University of California, Scripps Institution of Oceanography (SIO)
AHI-03-06	Ahi	2003	Assumed MSL	WGS 84 geographic	NOAA National Marine Fisheries Service (NMFS)
HI-05-03	Hi'ialakai	2005	Assumed MSL	WGS 84 geographic	NMFS
TUNE09WT	Thomas Washington	1992	Assumed MSL	WGS 84 geographic	SIO
KOK0319	Ka'imikai-O-Kanaloa	2003	Assumed MSL	WGS 84 geographic	NMFS

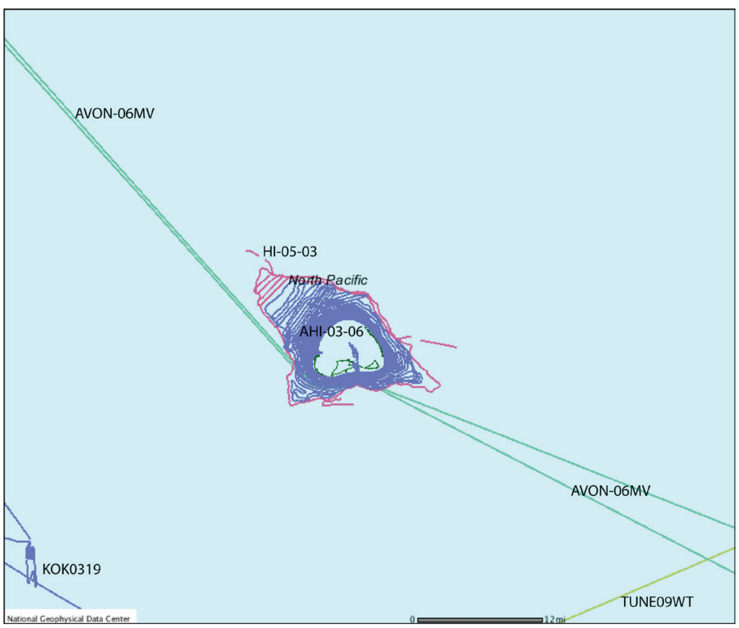

Figure 8. *Ship tracks of multibeam swath sonar surveys used in compiling the Midway Atoll DEMs.*

2. *MB-System* is an open source software package for the processing and display of bathymetry and backscatter imagery data derived from multibeam, interferometry, and sidescan sonars. The source code for *MB-System* is freely available (for free) by anonymous ftp (including "point and click" access through these web pages). A complete description is provided in web pages accessed through the web site. *MB-System* was originally developed at the Lamont-Doherty Earth Observatory of Columbia University (L-DEO) and is now a collaborative effort between the Monterey Bay Aquarium Research Institute (MBARI) and L-DEO. The National Science Foundation has provided the primary support for *MB-System* development since 1993. The Packard Foundation has provided significant support through MBARI since 1998. Additional support has derived from SeaBeam Instruments (1994-1997), NOAA (2002-2004), and others. URL: http://www.ldeo.columbia.edu/res/pi/MB-System[Extracted from *MB-System* web site.]

2) Trackline surveys

Twenty-eight single-beam echo-sounder surveys were available from the NGDC marine geophysical trackline database for use in the Midway Atoll DEMs (Table 6, Fig. 9). This database is comprised of bathymetry, magnetics, gravity, and seismic navigation data collected along ship tracks during marine cruises from 1961 to present. The data were downloaded as xyz files in WGS 84 and converted to MHW using *FME*.

The tracklines are spaced tens of kilometers apart and were only used where no high-resolution multibeam bathymetric data exist.

Table 6: Trackline surveys available in the Midway Atoll region.

Cruise ID	*Ship*	*Year*	*Original Vertical Datum*	*Original Horizontal Datum*	*Institution*
73102500	Kana Keoki	1973	Assumed MSL	WGS 84 geographic	University of Hawaii (HIG)
75072600	Kana Keoki	1975	Assumed MSL	WGS 84 geographic	HIG
76080601	Kana Keoki	1976	Assumed MSL	WGS 84 geographic	HIG
76080602	Kana Keoki	1976	Assumed MSL	WGS 84 geographic	HIG
77031705	Kana Keoki	1977	Assumed MSL	WGS 84 geographic	HIG
77031706*	Kana Keoki	1977	Assumed MSL	WGS 84 geographic	HIG
80041401	Kana Keoki	1980	Assumed MSL	WGS 84 geographic	HIG
80041402	Kana Keoki	1980	Assumed MSL	WGS 84 geographic	HIG
84042805	Kana Keoki	1984	Assumed MSL	WGS 84 geographic	HIG
KK720702	Kana Keoki	1972	Assumed MSL	WGS 84 geographic	HIG
KH7402	Hakuho Maru	1974	Assumed MSL	WGS 84 geographic	Ocean Research Institute, University of Tokyo
V2005	Vema	1964	Assumed MSL	WGS 84 geographic	Lamont-Doherty Geological Observatory
V2006	Vema	1964	Assumed MSL	WGS 84 geographic	Lamont-Doherty Geological Observatory
V2404	Vema	1967	Assumed MSL	WGS 84 geographic	Lamont-Doherty Geological Observatory
V2405	Vema	1967	Assumed MSL	WGS 84 geographic	Lamont-Doherty Geological Observatory
POL7201	Oceanographer	1972	Assumed MSL	WGS 84 geographic	NOAA
CMAPPI7E	Pioneer	1961	Assumed MSL	WGS 84 geographic	NOS
CMAPSU7E	Surveyor	1963	Assumed MSL	WGS 84 geographic	NOS
POL7004	Oceanographer	1970	Assumed MSL	WGS 84 geographic	NOAA POL
POL6829	Surveyor	1968	Assumed MSL	WGS 84 geographic	NOAA POL
STYX07AZ	Agassiz	1968	Assumed MSL	WGS 84 geographic	SIO
NOVA01AR	Argo	1967	Assumed MSL	WGS 84 geographic	SIO
TSDY03WT	Thomas Washington	1973	Assumed MSL	WGS 84 geographic	SIO
FARN0691	Farnella	1991	Assumed MSL	WGS 84 geographic	Natural Environment Research Council
FARN1091	Farnella	1991	Assumed MSL	WGS 84 geographic	Natural Environment Research Council
SI932003	Silas Bent	1971	Assumed MSL	WGS 84 geographic	US Navy Naval Oceanographic Office
SI932009	Silas Bent	1972	Assumed MSL	WGS 84 geographic	US Navy Naval Oceanographic Office
L876NP	Samuel P. Lee	1976	Assumed MSL	WGS 84 geographic	USGS Branch of Pacific Marine Geology

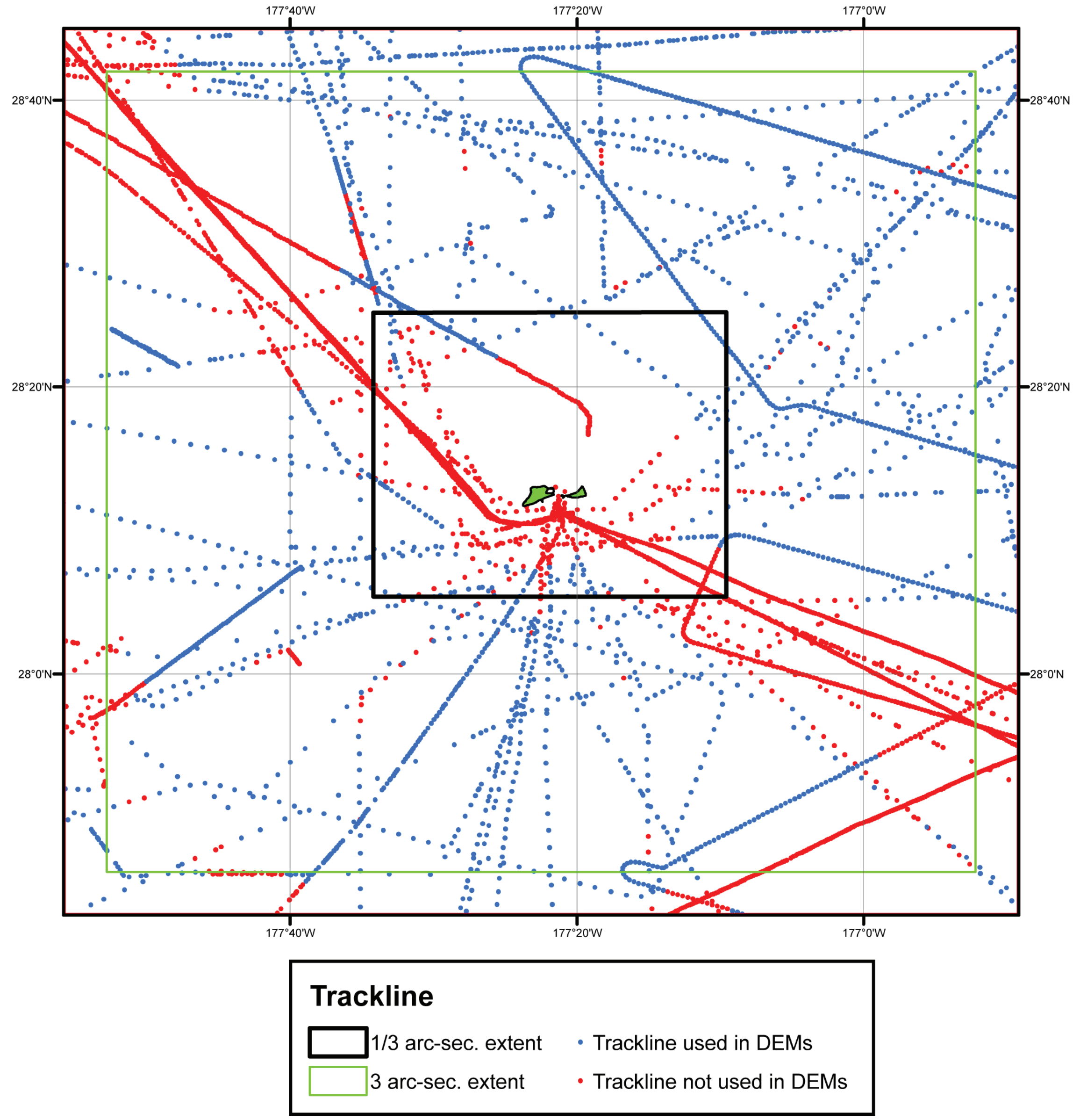

Figure 9. *Spatial coverage of trackline surveys in the Midway Atoll region. Trackline data shown in red were not used in the final DEM gridding, as there were high-resolution multibeam coverage or newer, more accurate trackline surveys available. Trackline data shown in blue were used for gridding of the final DEM.*

3) Naval Postgraduate School Estimated Depths

Graduate student Mark A. Camacho of NPS, completed his masters thesis on a depth analysis of Midway Atoll using high-resolution satellite imaging. Mr. Camacho's co-advisor, Dr. Richard Olsen, graciously provided NGDC with the resulting data.

Comancho used a high-resolution multispectral image taken from the QuickBird satellite in October 2004. *Environment for Visualizing Images 4.2* was used to analyze and process the image. Corrections were made for atmospheric absorption and scattering, the water column, and reflection from waves due to wind. Two separate bathymetric images were produced from two different algorithms for the main benthic classes: sand and coral.

Data were provided to NGDC as two xyz files, coral bottom and sand bottom. No vertical datum was documented, so NGDC assumed the data were essentially MSL. The xyz files were transformed to shapefiles and MHW using *FME* for assessing the data (Fig. 10). The data have a correlation of 86.5% between predicted depth and actual depths based on NOAA nautical chart values.

NPS estimated depth data are the most recent, high-resolution data, so were used instead of the CCMA bathymetric lidar (2001) and estimated depths (2002), or the 1941 NOS surveys.

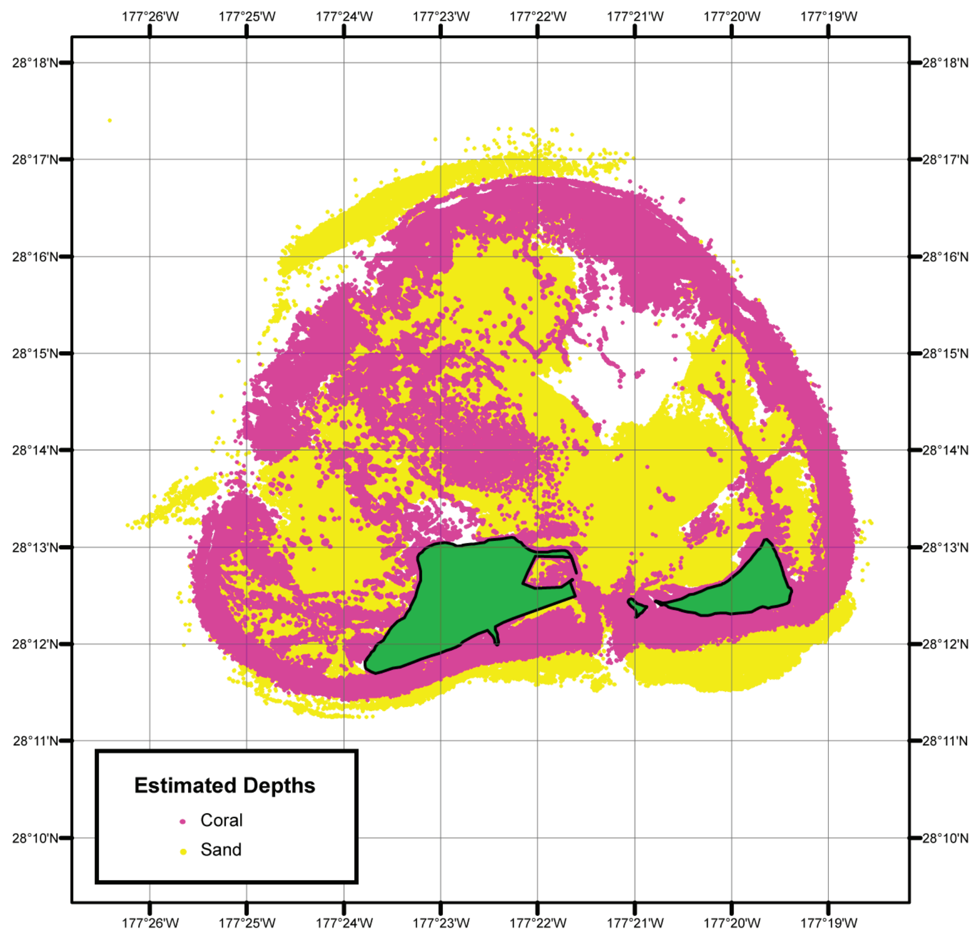

Figure 10. *Spatial coverage of estimated depths from NPS. Yellow represents a sandy bottom; pink represents coral cover.*

4) NGDC-digitized depths

NGDC digitized Nero Seamount from the NOAA RNC #19840 in the southwestern area of the 3 arc-second DEM (Fig. 11). Multibeam swath sonar survey KOK0319 covered the area, but had bad returns that did not accurately reflect the seamount, so it was not used.

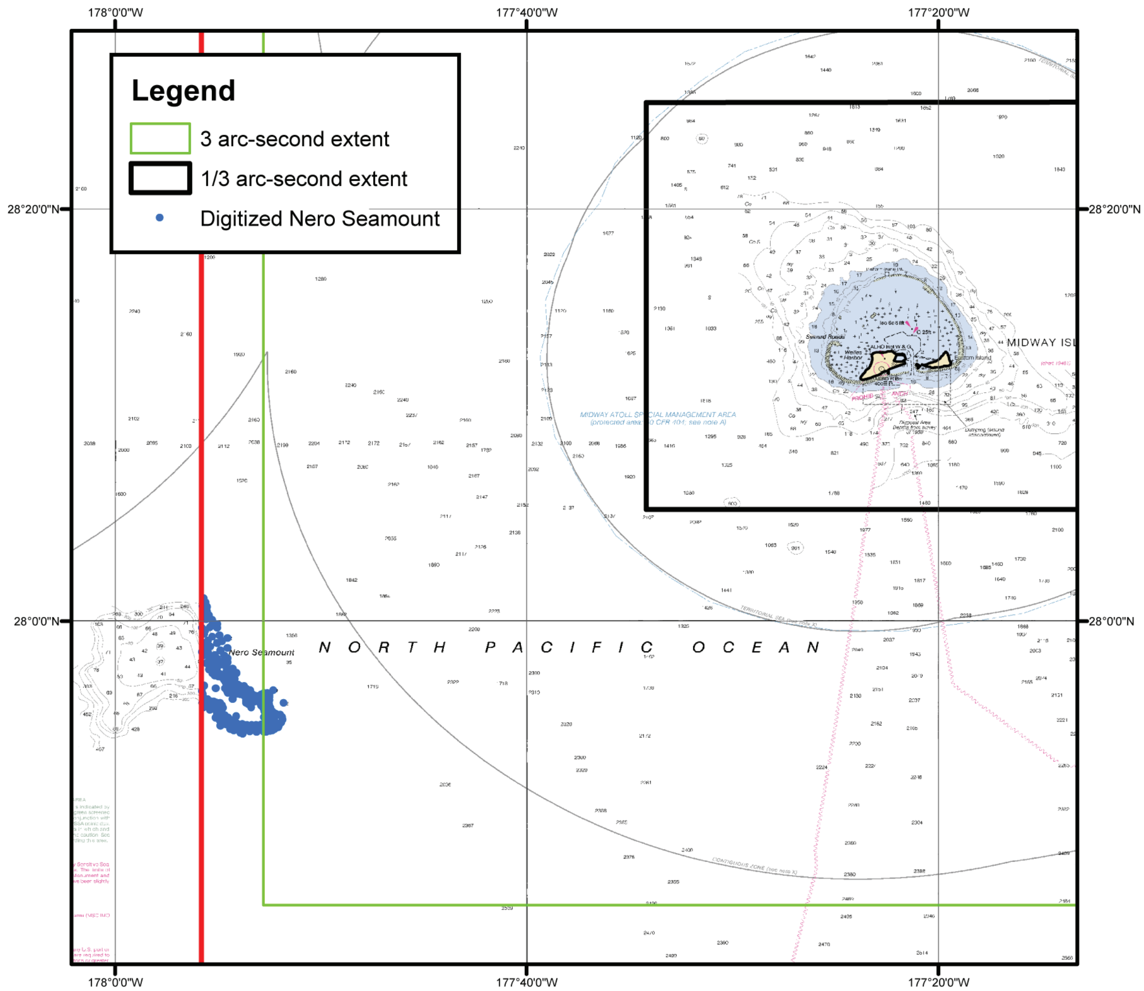

Figure 11. Soundings on Nero Seamount digitized from NOAA RNC #19840.

3.1.3 *Topography*

The NASA Space Shuttle Radar Topography (SRTM) 1 arc-second DEM provided full coverage of the islands and was used to build the Midway Atoll DEMs (Table 7; Fig. 12).

Table 7: Topographic dataset used in compiling the Midway Atoll DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
NASA	2000	Topographic DEM	1 arc-second	WGS 84 Geographic	WGS 84/EGM 96 Geoid	http://srtm.usgs.gov
NGDC	2009	Digitized Points		WGS 84 Geographic	MHW	

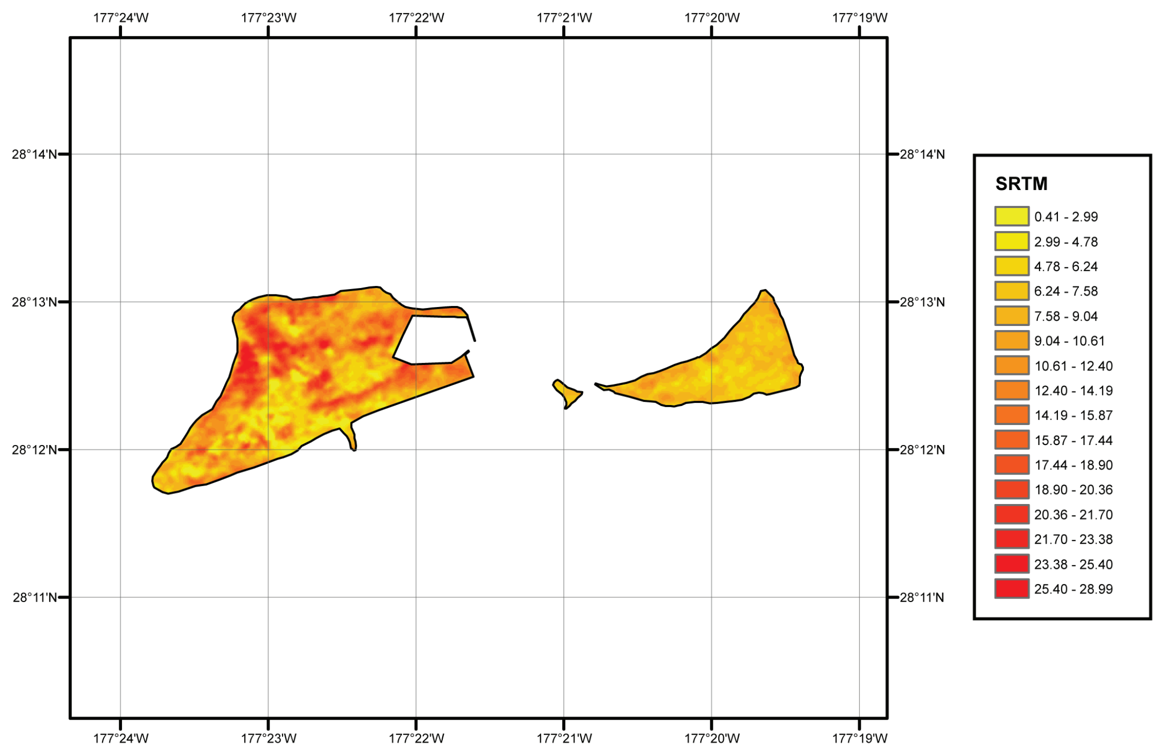

Figure 12. *SRTM data coverage for Midway Island. Coastline in black.*

1) NASA space shuttle radar topography

NASA SRTM obtained elevation data on a near-global scale to generate the most complete high-resolution digital topographic database of Earth[3]. The SRTM consisted of a specially modified radar system that flew onboard the Space Shuttle Endeavour during an 11-day mission in February of 2000. Data from this mission have been processed into 1 degree x 1 degree tiles that have been edited to define the coastline, and are available from the USGS Seamless web site (http://seamless.usgs.gov) as raster DEMs. The data have not been processed to bare earth, and have absolute horizontal and vertical accuracies of 20 and 16 meters, respectively.

A topographic surface was created with GMT to resample the SRTM from 1 arc-second to 1/3 arc-second. This created a smoother fit along the coastline when the SRTM DEM was clipped to the coast to delete values over the open ocean. The clipped data were converted into an xyz format for the final gridding process.

2) NGDC-digitized breakwater

NGDC digitized elevation points at 0.5 meters along the breakwater to the harbor (Figure 13). The width of the breakwater is ~5-6 meters, less than the width of one cell size for a 1/3 arc-second grid. A few points were digitized to create a continuous wall above MHW in the DEM, to avoid "channels" of water between cells representing the breakwater.

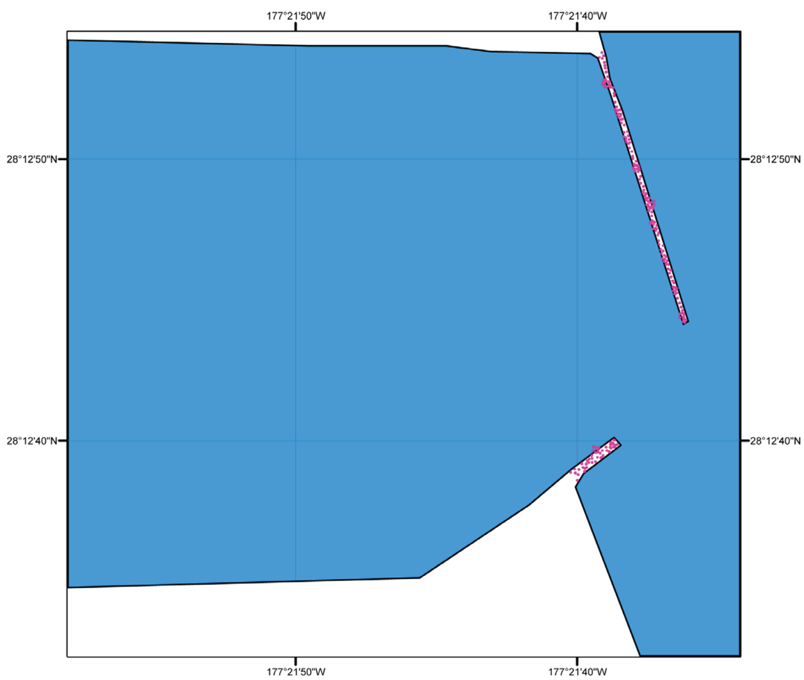

Figure 13. *Digitized points (in pink) on the breakwaters around the boat harbor. Coastline in black.*

3. The SRTM data sets result from a collaborative effort by the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA – previously known as the National Imagery and Mapping Agency, or NIMA), as well as the participation of the German and Italian space agencies, to generate a near-global digital elevation model (DEM) of the Earth using radar interferometry. The SRTM instrument consisted of the Spaceborne Imaging Radar-C (SIR-C) hardware set modified with a Space Station-derived mast and additional antennae to form an interferometer with a 60 meter long baseline. A description of the SRTM mission can be found in Farr and Kobrick (2000). Synthetic aperture radars are side-looking instruments and acquire data along continuous swaths. The SRTM swaths extended from about 30 degrees off-nadir to about 58 degrees off-nadir from an altitude of 233 km, and thus were about 225 km wide. During the data flight the instrument was operated at all times the orbiter was over land and about 1000 individual swaths were acquired over the ten days of mapping operations. Length of the acquired swaths range from a few hundred to several thousand km. Each individual data acquisition is referred to as a "data take." SRTM was the primary (and pretty much only) payload on the STS-99 mission of the Space Shuttle Endeavour, which launched February 11, 2000 and flew for 11 days. Following several hours for instrument deployment, activation and checkout, systematic interferometric data were collected for 222.4 consecutive hours. The instrument operated almost flawlessly and imaged 99.96% of the targeted landmass at least one time, 94.59% at least twice and about 50% at least three or more times. The goal was to image each terrain segment at least twice from different angles (on ascending, or north-going, and descending orbit passes) to fill in areas shadowed from the radar beam by terrain. This 'targeted landmass' consisted of all land between 56 degrees south and 60 degrees north latitude, which comprises almost exactly 80% of Earth's total landmass. [Extracted from SRTM online documentation]

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the Midway Atoll DEMs were originally referenced to vertical datums of mean lower low water (MLLW), MSL, and WGS 84/EGM 96 Geoid. All datasets were transformed to MHW to provide the maximum flooding scenario for inundation modeling.

1) **Bathymetric data**

   The multibeam, trackline surveys, and estimated depths were transformed from MSL to MHW using *FME* software, by adding a constant offset of -0.132 meters measured at the Midway Island NOAA tidal station #1619910 (Table 8; http://tidesandcurrents.noaa.gov).

2) **Topographic data**

   The SRTM topographic DEM was originally in WGS 84/EGM 96 Geoid vertical datum. There are no survey markers near Midway Island that relate this datum to the local tidal datum. Thus, we assumed the datum to be essentially equivalent to MSL in this area (Table 8). Conversion to MHW was accomplished by adding a constant value of -0.132 meters.

Table 8: Relationship between mean high water and other vertical datums in the Midway Atoll region.*

Vertical Datums	*Difference to MHW*
MSL	0.132 meters
MLLW	0.328 meters

*Datum relationships determined by NOAA tidal station 1619910 at Midway Island

3.2.2 Horizontal datum transformations

Datasets used to compile the Midway Atoll DEMs were originally referenced to WGS 84. No conversion was needed for the datasets in WGS 84. Datasets that were available but were not used for the final gridding process were referenced to UTM Zone 2 (CCMA) and undetermined horizontal datum (NOS). The relationship and transformational equations between WGS 84 and UTM Zone 2 are well established. These data were converted to WGS 84 using *FME* software. There was no defined relationship between the undetermined and WGS 84 datums, so smoothsheets of the NOS surveys were georeferenced in *ArcMap* and the data were manually shifted to visually match the smoothsheets.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

After vertical transformations were applied, the resulting ESRI shapefiles were checked in *ArcMap* for consistency between datasets. Problems and errors were identified and resolved before proceeding with subsequent gridding steps. The evaluated and edited ESRI shapefiles were then converted to xyz files in preparation for gridding. Problems included:

- Old NOS surveys in the shallow water with an undetermined horizontal datum.
- Estimated depths were the only recent data available for the shallow water region.
- Recent morphological changes due to the jetties at the boat harbor on Sand Island, constructed after surveys were conducted in the area.
- Limited high-resolution bathymetric measurements in the deep ocean surrounding the atoll.
- Lack of metadata for the lidar surveys and estimated depths from the Naval Postgraduate school, leading us to assume MSL vertical datum.

3.3.2 Smoothing of bathymetric data

Two “pre-surface” bathymetric grids were generated for the Midway Atoll DEMs due to the varying resolution of data coverage in the deep ocean. The NGDC multibeam swath sonar surveys are high resolution with beam spacing approximately 10 meters apart, a marked contrast with the trackline surveys spaced 1 to 15 kilometers apart. NGDC created a 1 arc-second cell size bathymetric grid slightly larger than the 1/3 arc-second DEM extent, and a 3 arc-second cell size bathymetric grid slightly larger than the 3 arc-second DEM extent. The grids were generated using *GMT*[4], an NSF-funded shareware software application designed to manipulate data for mapping purposes.

The bathymetric point data were median-averaged using the *GMT* tool “blockmedian” to create 1 and 3 arc-second grids 0.05 degrees (~5%) larger than the final Midway Atoll DEM gridding extents. The *GMT* tool “surface” was then used to apply a tight spline tension to interpolate elevations for cells without data values. The *GMT* grid created by “surface” was converted into an ESRI Arc ASCII grid file, and clipped to the final coastline (to eliminate data interpolation into land areas). The resulting surface was compared with original soundings to ensure grid accuracy (Fig. 14) and exported as an xyz file for use in the final gridding process (see Table 9). The statistical analysis of the differences between the 1 arc-second bathymetric surface and the estimated depths from the coral layer show that the majority of the soundings are in agreement with the bathymetric surface. Depths with the greatest difference (-10 and +10 meters) are due to averaging of multiple, closely spaced depths.

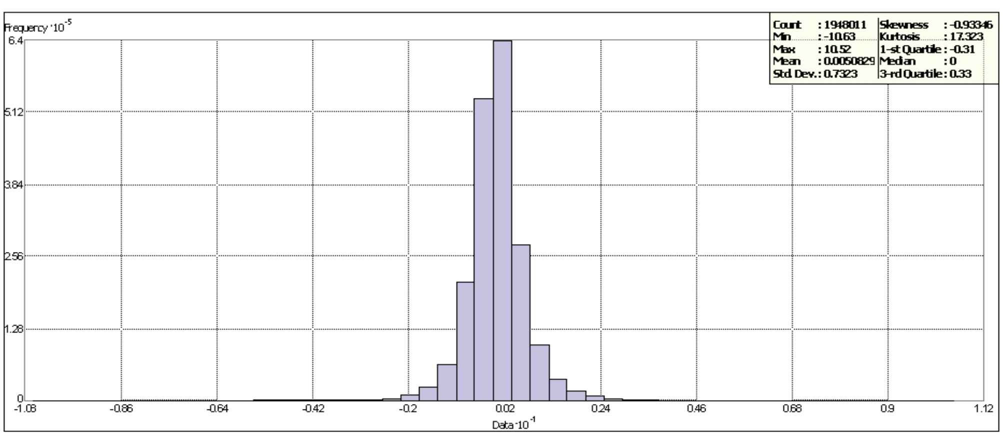

Figure 14. *Histogram of the differences between Naval Postgraduate School estimated depths from the coral layer and the 1 arc-second bathymetric grid.*

4. *GMT* is an open source collection of ~60 tools for manipulating geographic and Cartesian data sets (including filtering, trend fitting, gridding, projecting, etc.) and producing Encapsulated PostScript File (EPS) illustrations ranging from simple x-y plots via contour maps to artificially illuminated surfaces and 3-D perspective views. *GMT* supports ~30 map projections and transformations and comes with support data such as GSHHS coastlines, rivers, and political boundaries. *GMT* is developed and maintained by Paul Wessel and Walter H. F. Smith with help from a global set of volunteers, and is supported by the National Science Foundation. It is released under the GNU General Public License. URL: http://gmt.soest.hawaii.edu [Extracted from *GMT* web site.]

3.3.3 Gridding the data with MB-System

MB-System (http://www.ldeo.columbia.edu/res/pi/MB-System) was used to create the Midway Atoll DEMs. The *MB-System* tool "mbgrid" was used to apply a tight spline tension to the xyz data, and interpolate values for cells without data. The data hierarchy used in the "mbgrid" gridding algorithm, as relative gridding weights, is listed in Table 9. Greatest weight was given to the digitized features. Least weight was given to the coastline, trackline surveys, and the pre-surfaced bathymetric grid.

Table 9. Data hierarchy used to assign gridding weight in *MB-System*.

Dataset	*Relative Gridding Weight*
NGDC digitized features	1,000
NGDC Multibeam surveys	100
NPS Satellite Imagery Depths	100
SRTM Topographic DEM	10
1 arc-second Pre-surfaced bathymetric grid	1
NGDC Trackline	1
Midway Island coastline	1

3.4 Quality Assessment of the DEMs

3.4.1. Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Midway Atoll DEMs are dependent upon DEM cell size and the datasets used to determine corresponding DEM cell values. Topographic features have an estimated accuracy of no better than 30 meters (SRMT). Bathymetric features are resolved only to within a few kilometers in deep-water areas. Shallow, near-coastal regions have an accuracy approaching 10 meters (NPS). Positional accuracy is limited by the paucity of deep-water soundings and by recent morphologic change.

3.4.2 Vertical accuracy

Vertical accuracy of elevation values for the Midway Atoll DEMs are also highly dependent upon the source datasets contributing to DEM cell values. The SRTM topographic DEM has an estimated vertical accuracy between 10 and 16 meters. Bathymetric areas have an estimated accuracy of between 0.1 meters and 1% of water depth for the 1/3 arc-second DEM. The deep water values in the 3 arc-second DEM have an estimated accuracy of hundreds of meters due to gridding interpolation between sparse soundings.

3.4.3 Slope maps and 3-D perspectives

ESRI *ArcCatalog* was used to generate slope grids from the Midway Atoll DEMs to allow for visual inspection and identification of artificial slopes along boundaries between datasets (e.g., Fig. 15). The DEMs were transformed to UTM Zone 2 coordinates (horizontal units in meters) in *ArcCatalog* for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEMs. Three-dimensional viewing of the UTM-transformed DEMs was accomplished using ESRI *ArcScene* and *QT Modeler*. Figure 16 shows a perspective view of the 1/3 arc-second Midway Atoll DEM in its final version, created by *Persistence of Vision™ Raytracer (POV-Ray)*.

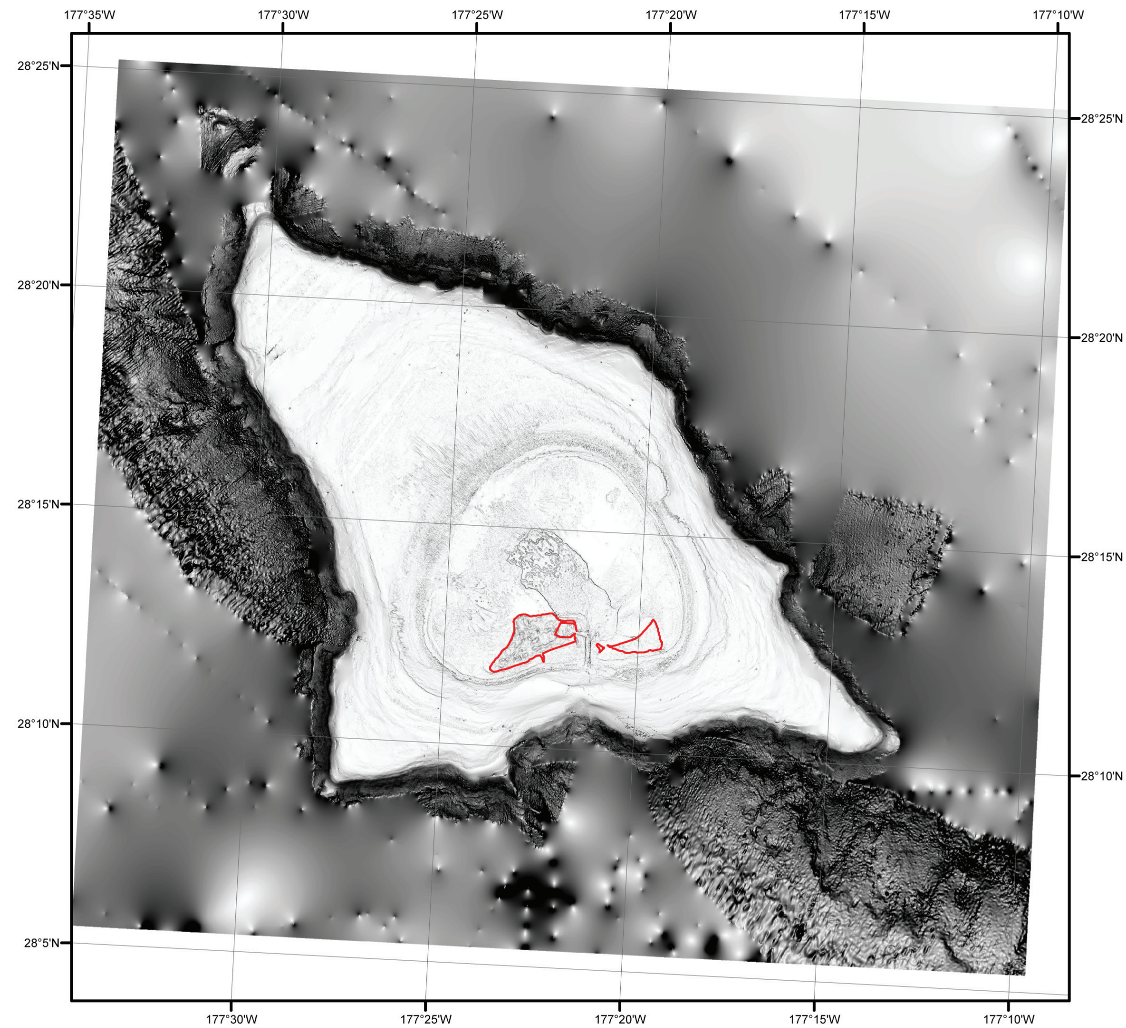

Figure 15. *Slope map of the 1/3 arc-second Midway Atoll DEM. Flat-lying slopes are white; dark shading denotes steep slopes; Midway Island coastline in red.*

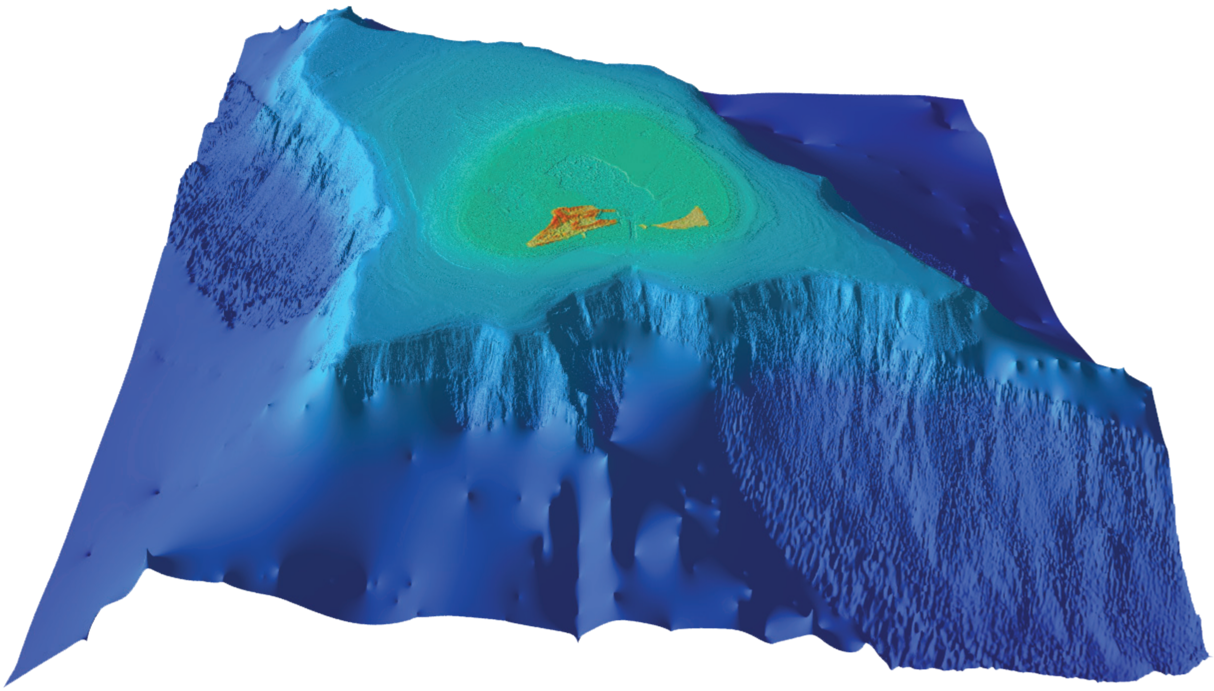

Figure 16. *Perspective view from the south of the 1/3 arc-second Midway Atoll DEM.
1.5x vertical exaggeration.*

3.4.4 Comparison with source data files

To ensure grid accuracy, the Midway Atoll DEMs were compared to select source data files. Files were chosen on the basis of their contribution to the grid-cell values in their coverage areas (i.e., had the greatest weight and did not significantly overlap other data files with comparable weight). A histogram of the differences between multibeam surveys and the 3 arc-second Midway Atoll DEM is shown in Figure 17. The greatest differences occurred along the edges of the deep-water swaths where the data are nosiest.

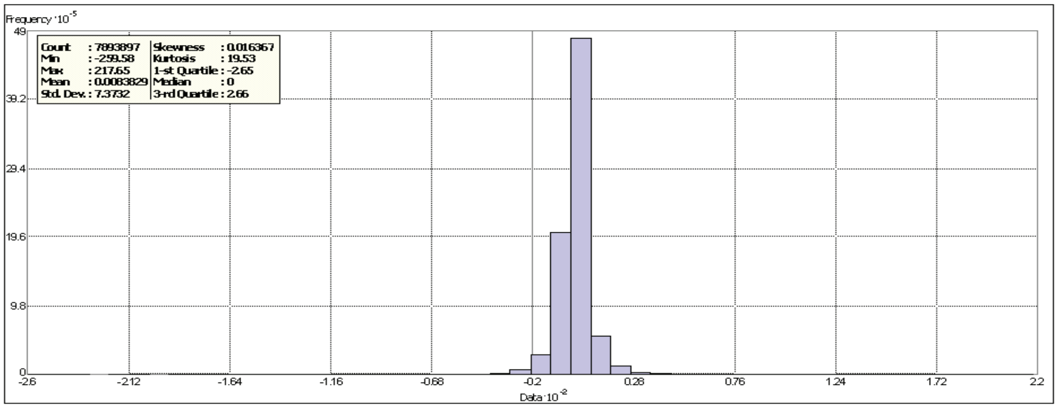

Figure 17. *Histogram of the differences between the NOAA National Marine Fisheries Service multibeam swath sonar surveys and the 3 arc-second Midway Atoll DEM.*

A histogram of the differences between the SRTM topographic DEM gridded to 1/3 arc-second and the 1/3 arc-second Midway DEM is shown in Figure 18. Differences range from -25 meters to 3 meters, where negative values indicate that elevations of the SRTM data are higher than the DEM elevations. The greatest differences occurred along the harbor coastline where the SRTM data (2000) were clipped to the present coastline.

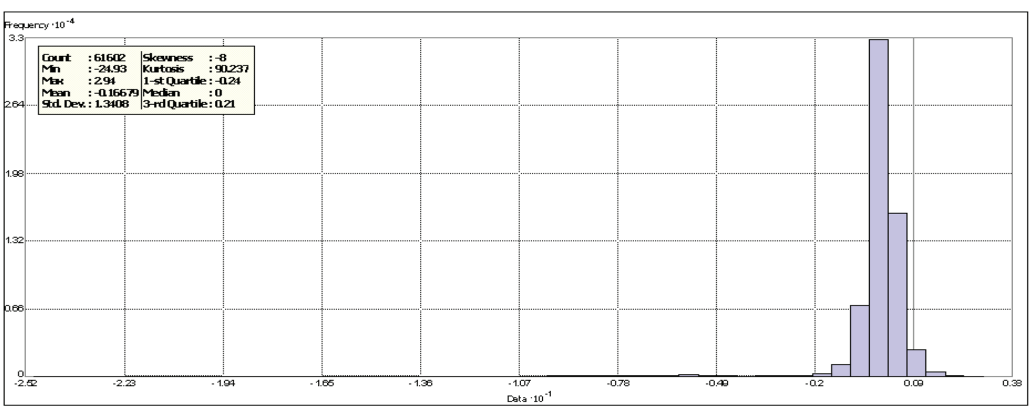

Figure 18. *Histogram of the differences between SRTM data and the 1/3 arc-second Midway Atoll DEM.*

4. Summary and Conclusions

Two integrated bathymetric–topographic digital elevation models of Midway Atoll, with cell spacing of 3 arc-seconds and 1/3 arc-seconds, were developed for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research. The best available digital data from U.S. federal agencies were obtained by NGDC, shifted to common horizontal and vertical datums, and evaluated and edited before DEM generation. The data were quality checked, processed and gridded using *ArcGIS, FME, GMT, MB-System*, and *Quick Terrain Modeler* software.

Recommendations to improve the Midway Atoll DEMs, based on NGDC's research and analysis, are listed below:

- Conduct hydrographic surveys in shallow-water areas inside the atoll.
- Conduct bathymetric–topographic lidar surveys of the entire atoll.
- Conduct multibeam swath sonar surveys of the deep ocean surrounding the atoll.
- Digitize NOAA Raster Nautical Charts as Electronic Nautical Charts.

5. Acknowledgments

The creation of the Midway Atoll DEMs was funded by the NOAA Pacific Marine Environmental Laboratory. The authors thank Nazila Merati, Marie Eble, and Vasily Titov (PMEL); and Ann Gibbs (USGS Pacific Science Center). We would also like to thank Richard Olsen and Mark Camacho (Naval Postgraduate School) for providing us with estimated depths data from Mark Camacho's thesis research, and Tim Battista and Richard Stumpf (CCMA) for providing the bathymetric lidar data and estimated depths from their studies.

6. References

Camacho Mark A., 2006. Depth analysis of Midway Atoll using quickbird multi-spectral imaging over variable substrates: MS Thesis Naval Postgraduate School.

Nautical Chart #19480 (RNC), 9th Edition, 2007. Gambia Shoal to Kure Atoll. Scale 1: 180,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #19481 (RNC), 11th Edition, 2005. Midway Islands. Scale 1: 32,500. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #19482 (RNC), 9th Edition, 2000. Midway Islands. Scale 1: 10,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

7. Data Processing Software

ArcGIS v. 9.2, developed and licensed by ESRI, Redlands, Oregon, http://www.esri.com

FME 2008 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada, http://www.safe.com

GEODAS v. 5 – Geophysical Data System, free software developed and maintained by Dan Metzger, NOAA National Geophysical Data Center, http://www.ngdc.noaa.gov/mgg/geodas

GMT v. 4.1.4 – Generic Mapping Tools, free software developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.edu

MB-System v. 5.1.0, free software developed and maintained by David W. Caress and Dale N. Chayes, funded by the National Science Foundation, http://www.ldeo.columbia.edu/res/pi/MB-System

Persistance of Vision Pty. Ltd,. (2004), Persistence of Vision™ Raytracer. Persistance of Vision Pty., Williamstown, Victoria, Australia, http://www.povray.org

Quick Terrain Modeler v. 6.0.1, Lidar processing software developed by John Hopkins University's Applied Physics Laboratory (APL) and maintained and licensed by Applied Imagery, http://www.appliedimagery.com